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Alexander

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(54) **WIRELESS RECEIVER**

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H03D 1/00 (2006.01)
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(52) **U.S. Cl.**

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(Continued)

(58) **Field of Classification Search**

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(56) **References Cited**

U.S. PATENT DOCUMENTS

7,277,506 B1	10/2007	Pope et al.		
7,298,778 B2 *	11/2007	Visoz	H04B 1/712	375/148

(Continued)

OTHER PUBLICATIONS

"Australian Application No. 2015904909, Search Report dated Oct. 21, 2016", (Oct. 21, 2016), 7 pgs.

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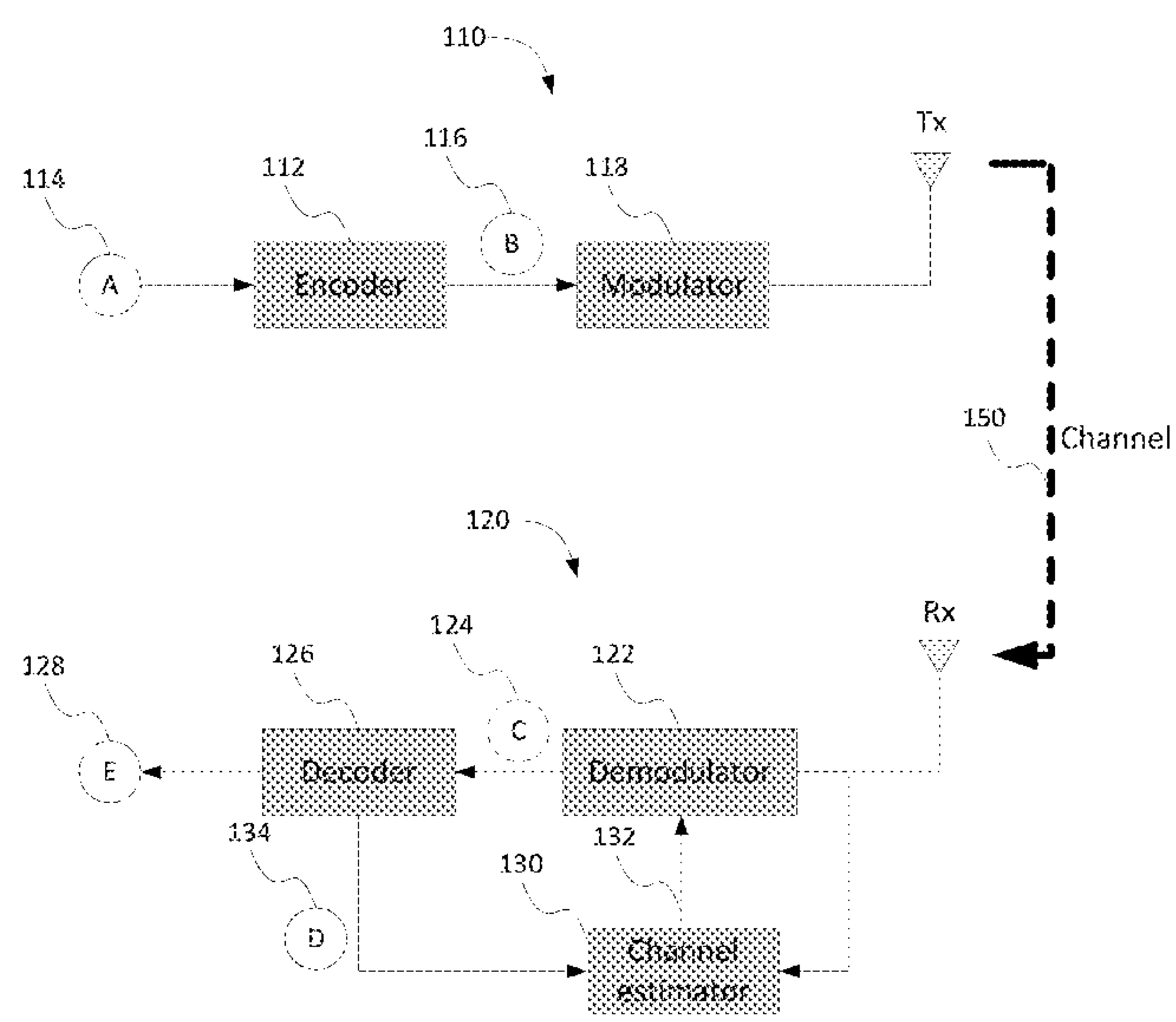
(57) **ABSTRACT**

The present invention relates to a method and apparatus for channel estimation between a transmitter and a receiver in a wireless communications system. In one arrangement, the method comprises: receiving at the receiver a first sequence of bits representing a first sequence of coded symbols transmitted over the communications channel; decoding the first sequence of coded symbols using maximum-likelihood based decoding including: generating traceback outcomes by tracing backwards the first sequence of bits through a maximum-likelihood based traceback path, the traceback outcomes including a first portion associated with a first traceback depth and a second portion associated with a second traceback depth that is deeper than the first traceback depth; generating a channel estimate of the communications channel based on the first portion of the traceback outcomes; and generating an estimate of at least some information bits coded in the first sequence of coded symbols based on the second portion of the traceback outcomes.

18 Claims, 9 Drawing Sheets



(51) **Int. Cl.**

H04L 25/02	(2006.01)
H03M 13/41	(2006.01)
H03M 13/00	(2006.01)
H04L 25/03	(2006.01)
H04L 27/26	(2006.01)
H03M 13/11	(2006.01)
H03M 13/29	(2006.01)
H04L 1/20	(2006.01)

(52) **U.S. Cl.**
CPC ***H03M 13/6337*** (2013.01); ***H04L 25/024*** (2013.01); ***H04L 25/03203*** (2013.01); ***H04L 25/03292*** (2013.01); *H03M 13/1102* (2013.01); *H03M 13/2957* (2013.01); *H03M 13/6362* (2013.01); *H04L 1/208* (2013.01); *H04L 27/2649* (2013.01)

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USPC 375/316, 324, 340, 341, 343, 346, 356
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,688,888 B2 * 3/2010 Brown H04L 25/03057 375/229
8,397,148 B2 3/2013 Shi et al.
8,948,321 B2 2/2015 Eliaz et al.
2006/0239342 A1 * 10/2006 Amizic H04L 25/0212 375/233
2007/0104264 A1 * 5/2007 Park H04L 1/0071 375/233
2007/0183489 A1 * 8/2007 Zhidkov H03M 13/256 375/229
2007/0237263 A1 * 10/2007 Strolle H04H 20/28 375/321
2008/0008233 A1 * 1/2008 Cohen H04L 25/0212 375/232
2008/0008272 A1 * 1/2008 Yang H03M 13/2933 375/341
2008/0175309 A1 * 7/2008 Fimoff H04L 25/03019 375/232
2010/0269026 A1 * 10/2010 Yang H03M 13/4138 714/792
2011/0243212 A1 * 10/2011 Kim H04L 25/03057 375/232
2011/0268168 A1 * 11/2011 Dybdal H04L 25/03171 375/225
2013/0198594 A1 * 8/2013 Catthoor H03M 13/256 714/792
2014/0056387 A1 * 2/2014 Asahina H04L 1/006 375/340
2016/0164633 A1 * 6/2016 Avner H04L 1/0054 375/233

* cited by examiner

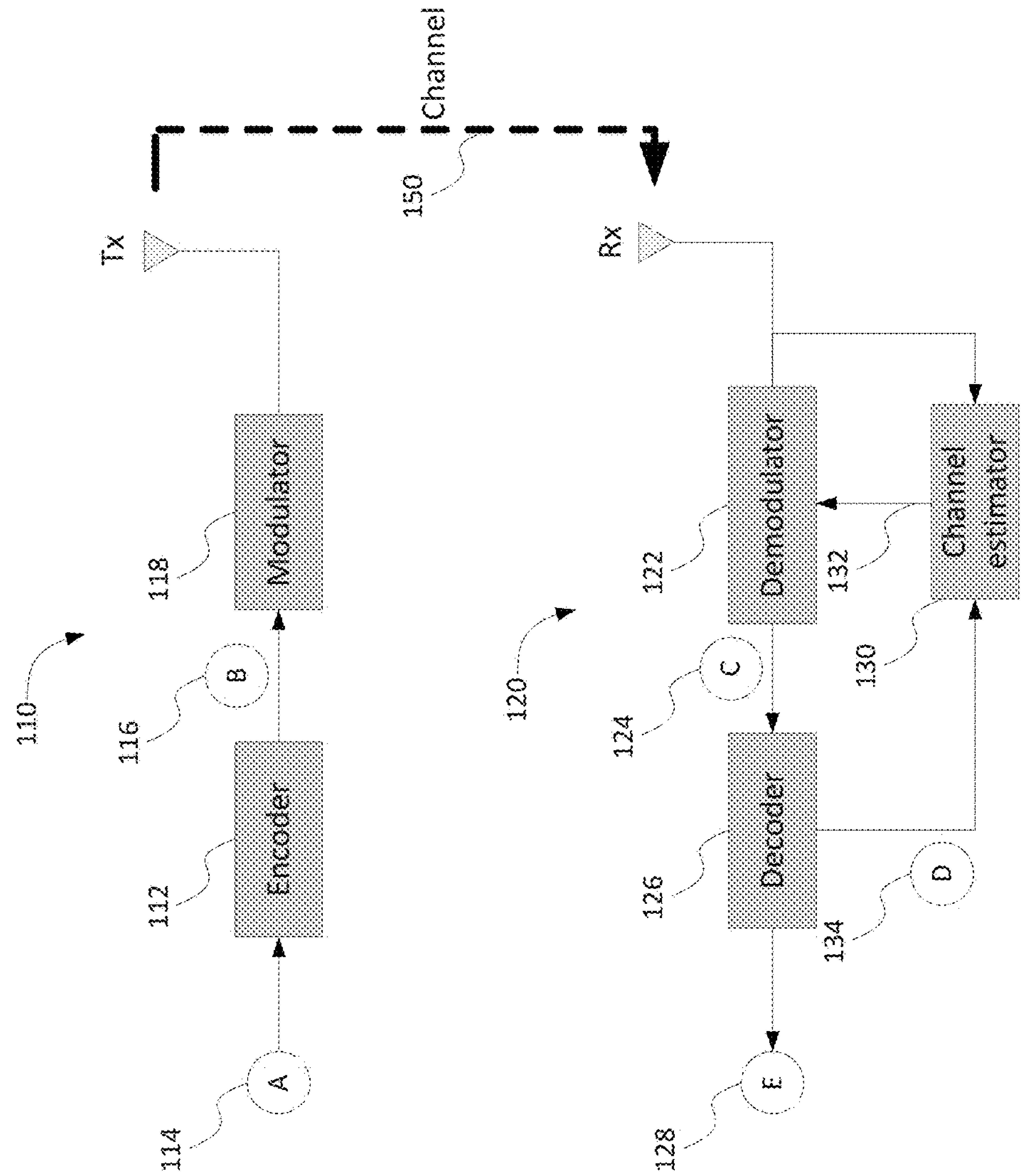
Channel
150
Tx
Rx
110
120
A
114
Encoder
112
B
116
Modulator
118
Demodulator
122
C
124
Decoder
126
E
128
D
134
Channel estimator
130
132

Figure 1

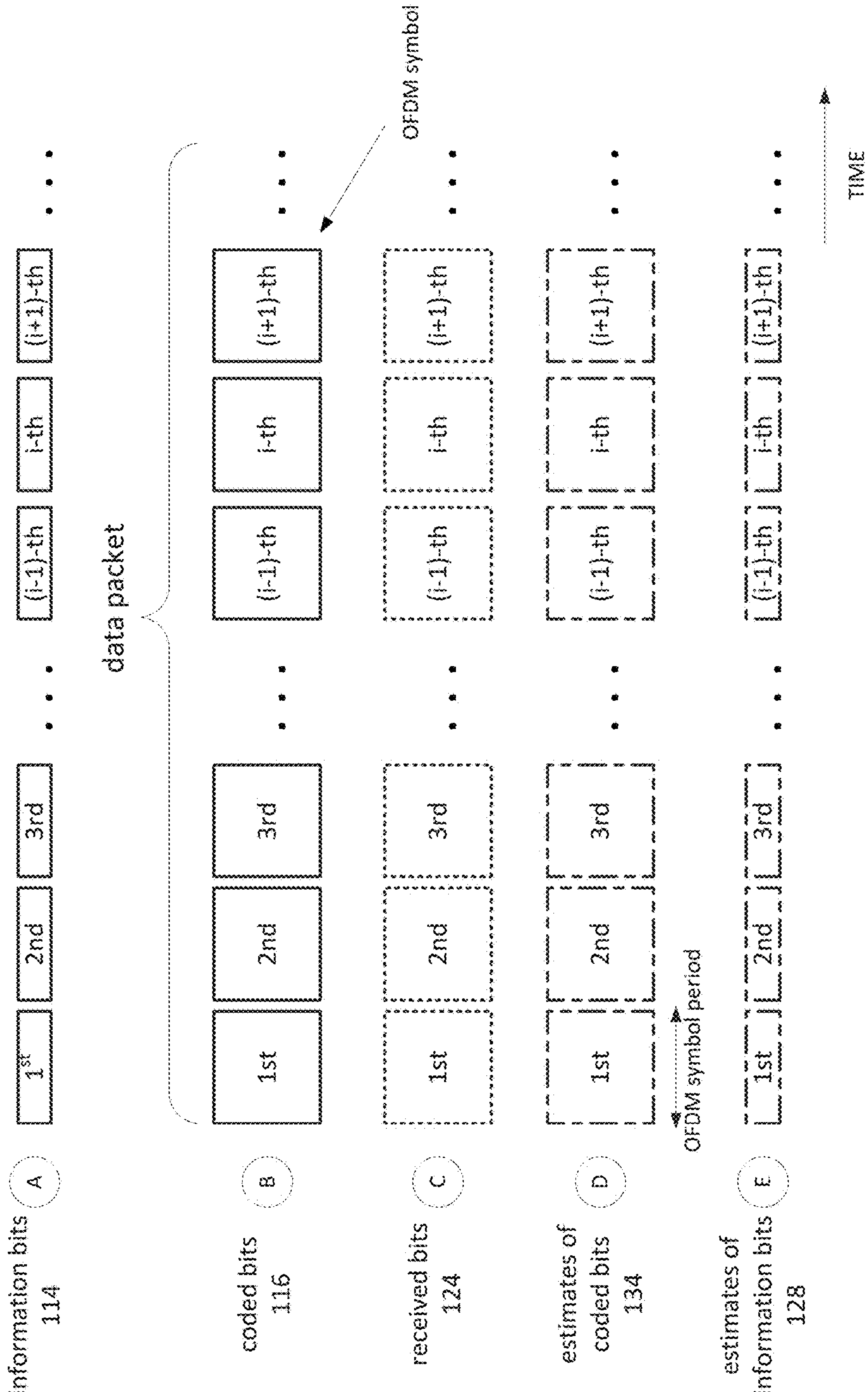
information bits
114
A
1st
2nd
3rd
(i-1)-th
i-th
(i+1)-th
data packet
coded bits
116
B
received bits
124
C
estimates of
coded bits
134
D
OFDM symbol period
estimates of
information bits
128
E
OFDM symbol
TIME

Figure 2

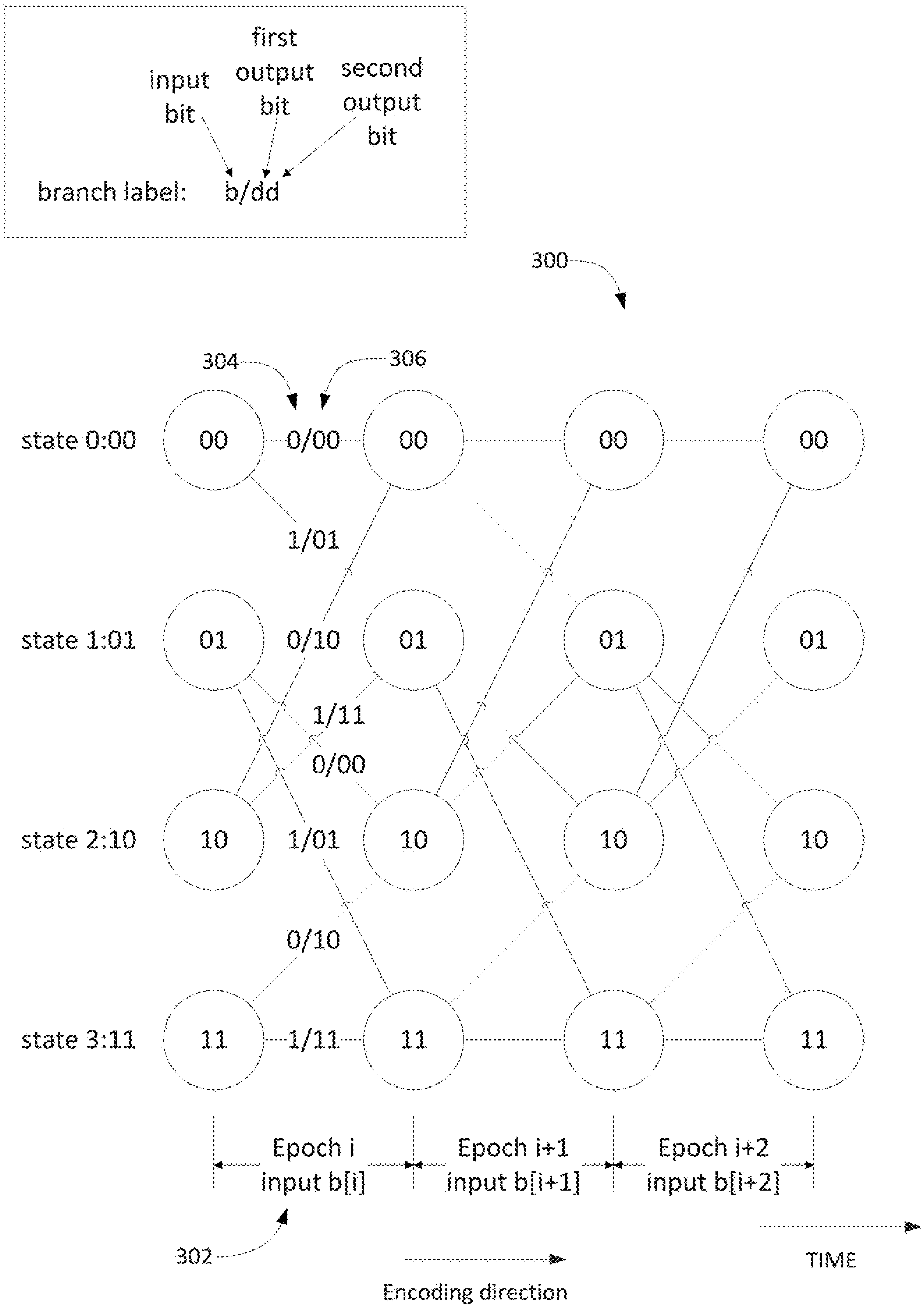
first
input bit
output bit
second output bit
branch label: b/dd
300
304
306
state 0:00
state 1:01
state 2:10
state 3:11
00
01
10
11
0/00
1/01
0/10
1/11
0/00
1/01
0/10
1/11
Epoch i input b[i]
Epoch i+1 input b[i+1]
Epoch i+2 input b[i+2]
302
Encoding direction
TIME

Figure 3A

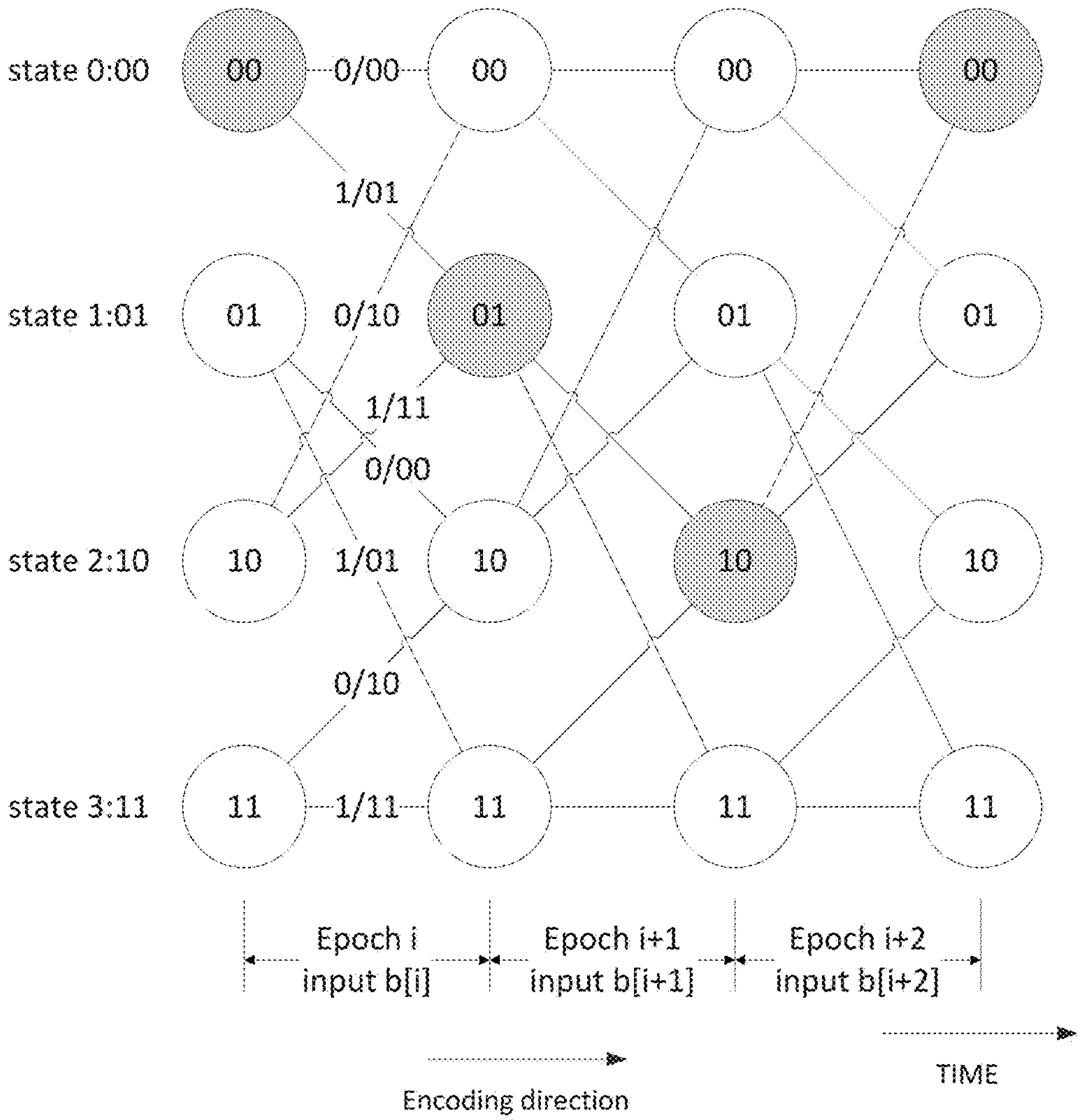
state 0:00
state 1:01
state 2:10
state 3:11
00
01
10
11
0/00
1/01
0/10
1/11
0/00
1/01
0/10
1/11
Epoch i
input b[i]
Epoch i+1
input b[i+1]
Epoch i+2
input b[i+2]
Encoding direction
TIME

Figure 3B

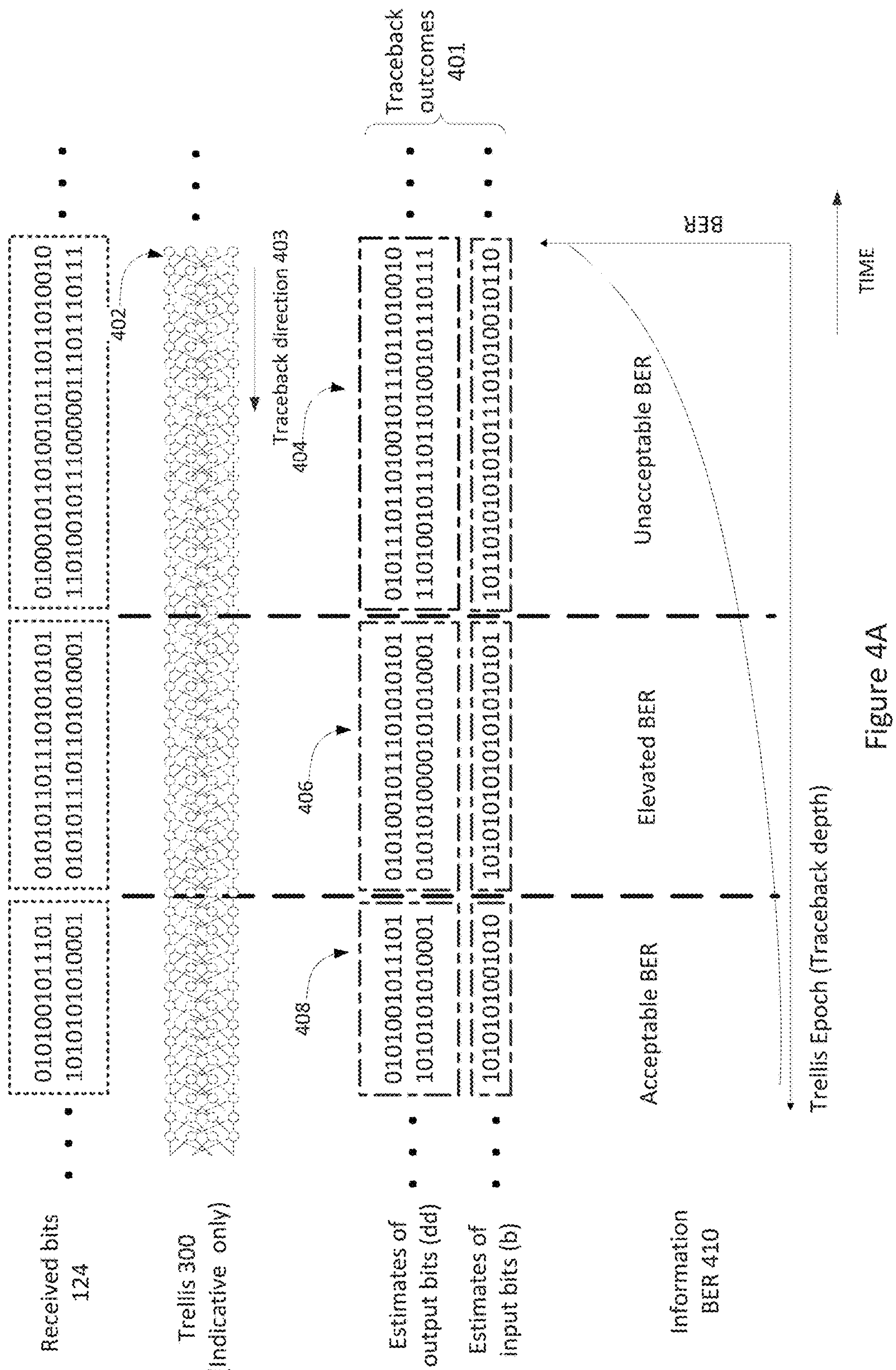
Received bits 124
Trellis 300 (Indicative only)
Estimates of output bits (dd)
Estimates of input bits (b)
Information BER 410
Traceback outcomes 401
402
Traceback direction 403
404
406
408
Acceptable BER
Elevated BER
Unacceptable BER
Trellis Epoch (Traceback depth)
BER
TIME

Figure 4A

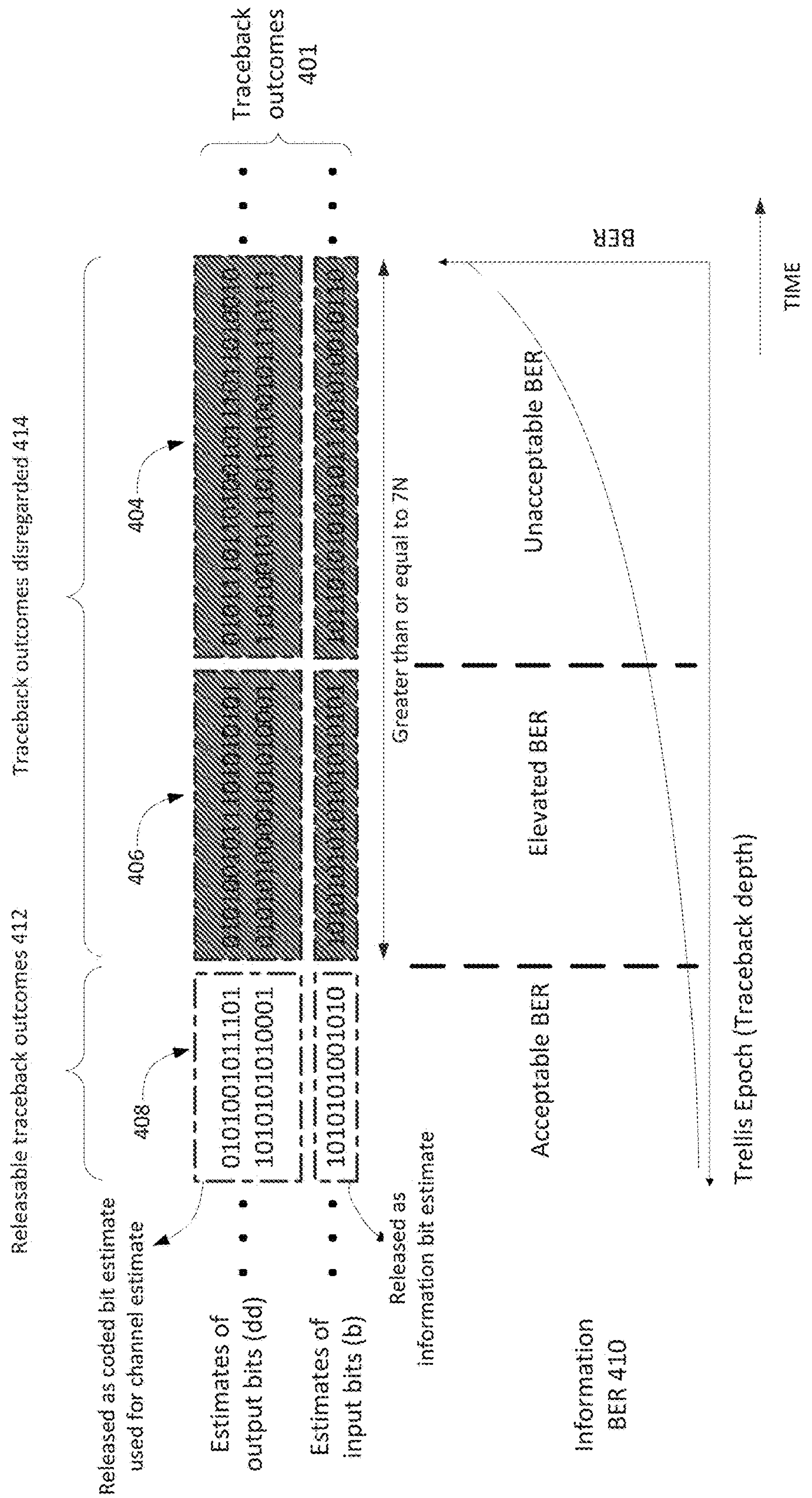

Figure 4B
(prior art)

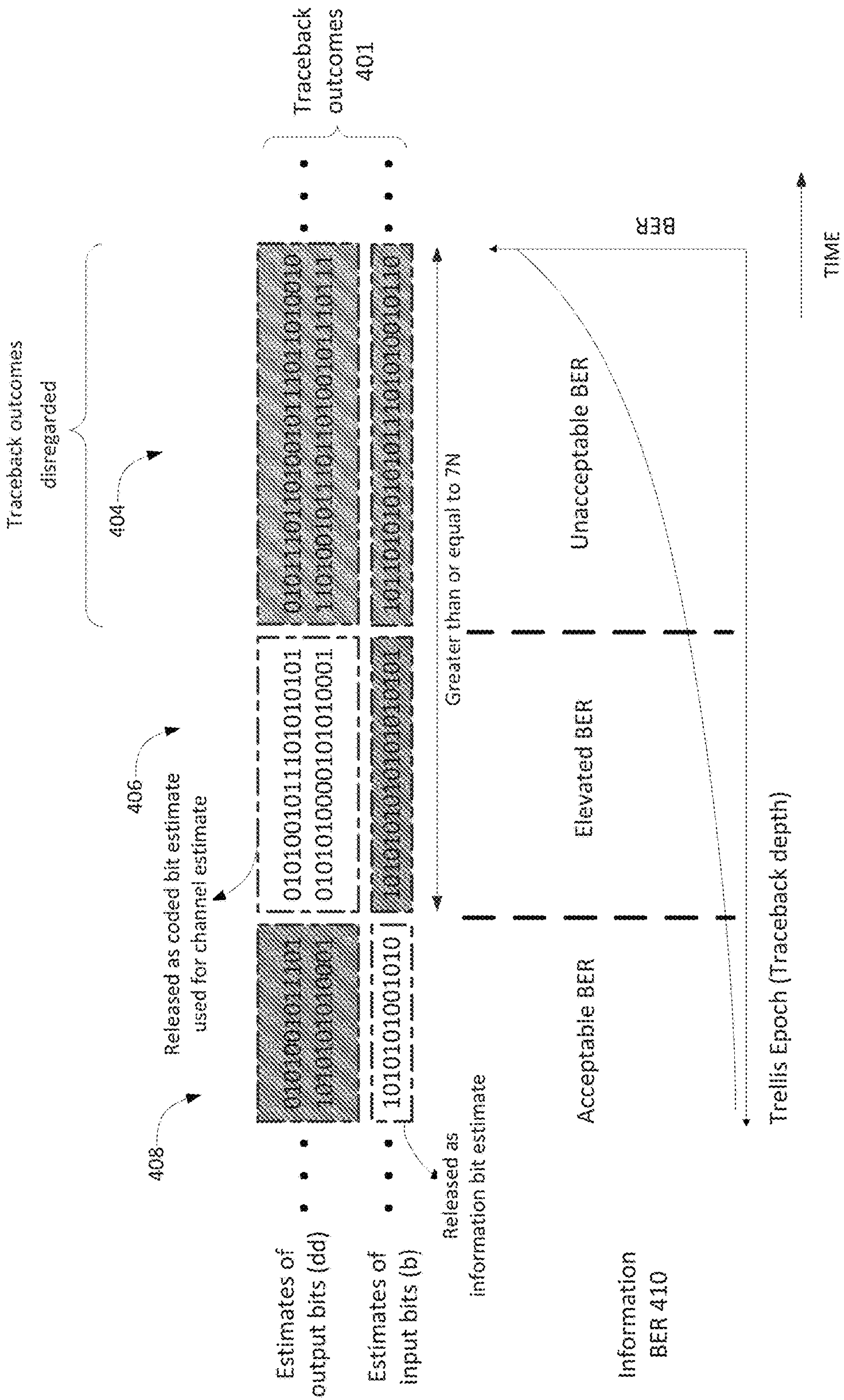
Traceback outcomes 401
Traceback outcomes disregarded
404
406
Released as coded bit estimate used for channel estimate
408
Estimates of output bits (dd)
Estimates of input bits (b)
Released as information bit estimate
Information BER 410
Acceptable BER
Elevated BER
Unacceptable BER
Greater than or equal to 7N
Trellis Epoch (Traceback depth)
BER
TIME

Figure 4C

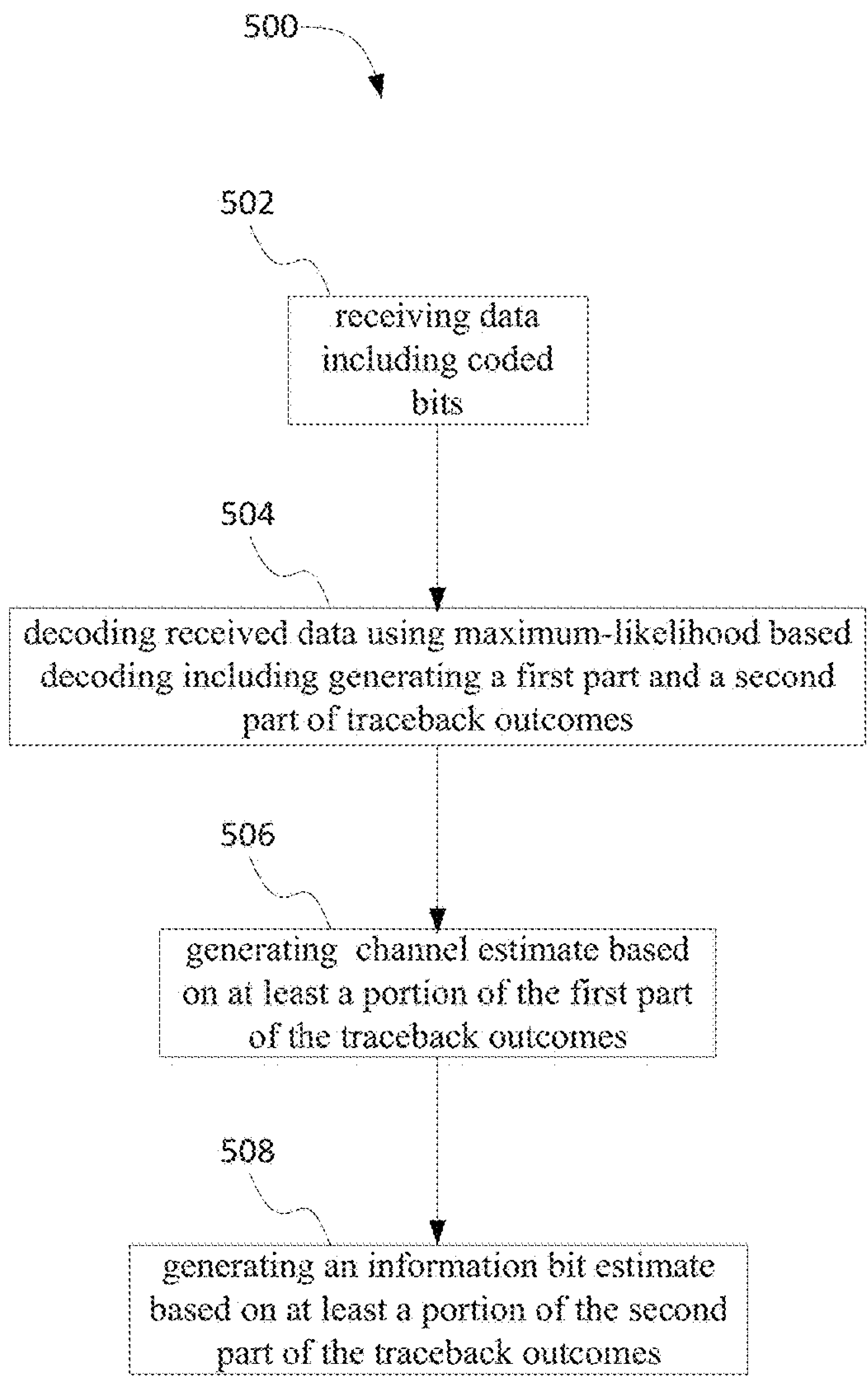
500
502
receiving data including coded bits
504
decoding received data using maximum-likelihood based decoding including generating a first part and a second part of traceback outcomes
506
generating channel estimate based on at least a portion of the first part of the traceback outcomes
508
generating an information bit estimate based on at least a portion of the second part of the traceback outcomes

Figure 5

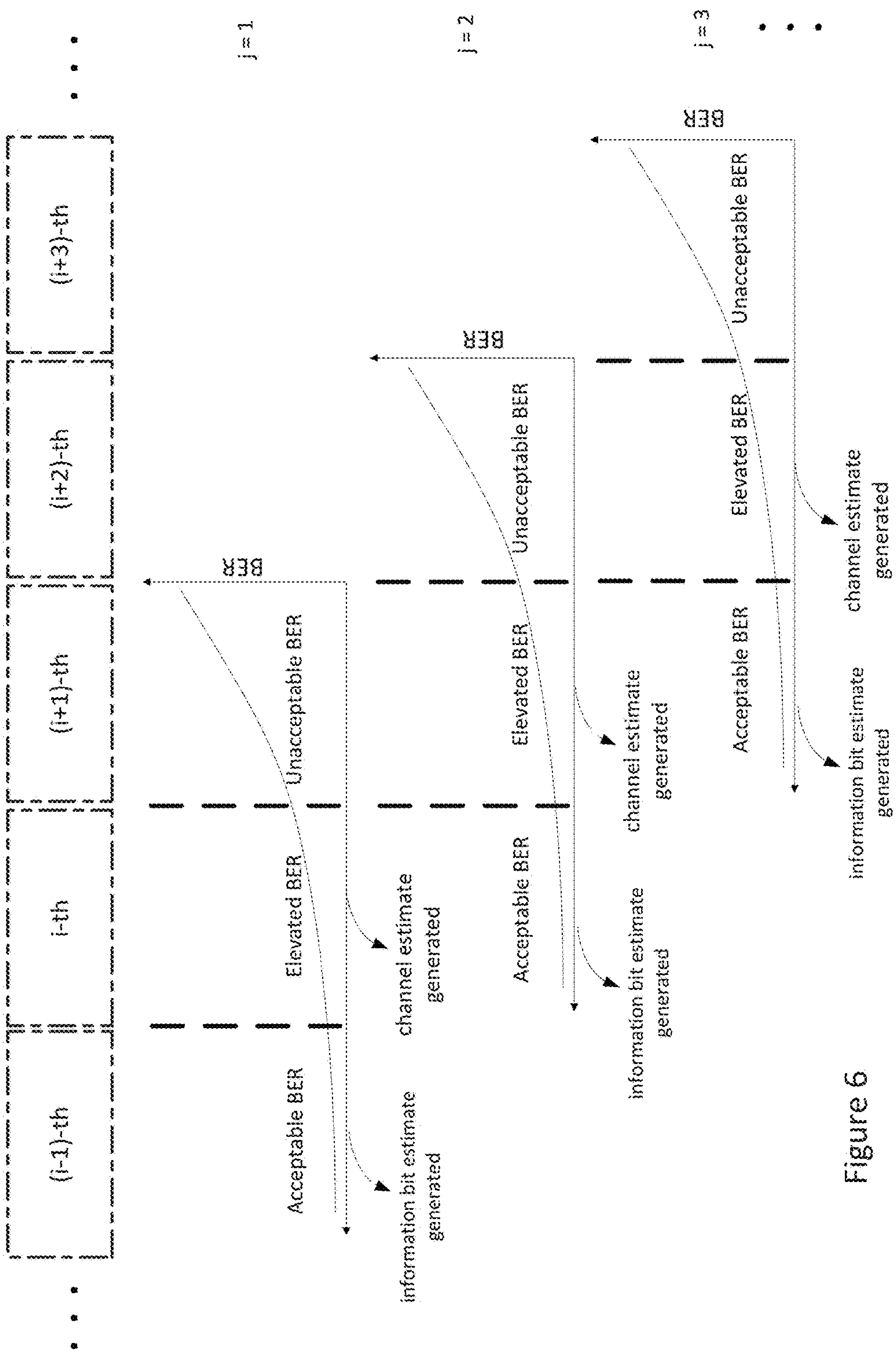
(i-1)-th
i-th
(i+1)-th
(i+2)-th
(i+3)-th
j = 1
j = 2
j = 3
BER
Unacceptable BER
Elevated BER
Acceptable BER
channel estimate generated
information bit estimate generated
BER
Unacceptable BER
Elevated BER
Acceptable BER
channel estimate generated
information bit estimate generated
BER
Unacceptable BER
Elevated BER
Acceptable BER
channel estimate generated
information bit estimate generated

Figure 6

WIRELESS RECEIVER

CLAIM OF PRIORITY

This application claims the benefit of priority of Australia Patent Application No. 2015904909, filed on Nov. 27, 2015, the benefit of priority of which is claimed hereby, and which is incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

The present invention relates to a method and apparatus for channel estimation in a wireless communications system.

BACKGROUND OF THE INVENTION

In OFDM based communications systems operating in mobile outdoor radio environments it is advantageous to use decoder outcomes to assist with estimating a communications channel Decoder outcomes are outcomes from a decoder including estimates of the underlying information bit stream and, in some cases, estimates of the output from the corresponding encoder. The estimated channel can then be used to demodulate the received signal, even if the channel is changing during receipt of a data packet.

A data packet typically includes a known initial segment, called a preamble, that allows an initial channel estimate to be formed. A channel estimator uses this preamble-based channel estimate to decode at least the earlier parts of the payload (i.e. the data bearing segment of the data packet following the preamble). Once decoding is performed on the earlier parts of the payload, the channel estimate may be updated based on the decoder outcomes, and may therefore be tracked during receipt of later parts of the payload.

Reference to any prior art in the specification is not, and should not be taken as, an acknowledgment or any form of suggestion that this prior art forms part of the common general knowledge in any jurisdiction or that this prior art could reasonably be expected to be understood, regarded as relevant and/or combined with other pieces of prior art by a person skilled in the art.

SUMMARY OF THE INVENTION

According to a first aspect of the invention there is provided a method of estimating a communications channel between a transmitter and a receiver, the method comprising: receiving at the receiver a first sequence of bits representing a first sequence of coded symbols transmitted over the communications channel; decoding the first sequence of coded symbols using maximum-likelihood based decoding including: generating traceback outcomes by tracing backwards the first sequence of bits through a maximum-likelihood based traceback path, the traceback outcomes including a first portion associated with a first traceback depth and a second portion associated with a second traceback depth that is deeper than the first traceback depth; generating a channel estimate of the communications channel based on the first portion of the traceback outcomes; and generating an estimate of at least some information bits coded in the first sequence of coded symbols based on the second portion of the traceback outcomes.

The first portion may be subject to a first information bit error rate (BER) and the second portion may be subject to a second information BER that is lower than the first information BER.

The method may further comprise disregarding any estimate of the information bits generated based on the first portion of the traceback outcomes.

The step of generating a channel estimate of the communications channel may commence after generation of the first portion of the traceback outcomes and before completion of generation of the second portion of the traceback outcomes.

The step of generating an estimate of information bits may commence after completion of generation of the second portion of the traceback outcomes.

The traceback outcomes may include a third portion that is associated with a third traceback depth that is shallower than the second traceback depth, and that is subject to a third information BER that is higher than the first information BER, and the method may further comprise: disregarding any estimate of information bits generated based on the third portion of the traceback outcomes; and disregarding any estimate of a transmitted coded symbol generated based on the third portion of the traceback outcomes.

The step of generating a channel may include generating an estimate of at least one of the first sequence of transmitted coded symbols based on the first portion of the traceback outcomes.

The step of generating a channel may include: generating an estimate of information bits coded in the coded symbols based on the first portion of the traceback outcomes; and re-encoding the estimate of the information bits to form re-encoded symbols.

The method may further comprise: receiving at the receiver a second sequence of bits representing a second sequence of coded symbols and including at least part of the first sequence of bits; decoding the second sequence of coded symbols using maximum-likelihood based decoding including: generating further traceback outcomes by tracing backwards the second sequence of bits through a maximum-likelihood based traceback path, the further traceback outcomes including a fourth portion associated with a fourth traceback depth and a fifth portion associated with a fifth traceback depth that is deeper than the fourth traceback depth, generating an updated channel estimate of the communications channel based on the fourth portion of the further traceback outcomes; and generating an estimate of at least some information bits coded in the second sequence of coded symbols based on the fifth portion of the further traceback outcomes. The method may further comprise disregarding any estimate of the information bits generated based on the fourth portion of the further traceback outcomes.

The further traceback outcomes may include a sixth portion that is associated with a sixth traceback depth that is shallower than the fourth traceback depth, and that is subject to a sixth information BER that is higher than the fourth information BER, the method further comprising: disregarding any estimate of information bits generated based on the sixth portion of the further traceback outcomes; and disregarding any estimate of a transmitted coded symbol generated based on the sixth portion of the further traceback outcomes.

The second and/or the fifth traceback depth may be no less than approximately 7N, where N is the encoding constraint length.

Any one or more of the first portion, the second portion correspond to one or more OFDM symbols, the fourth portion and the fifth portion may correspond to one or more OFDM symbols.

The first and/or the second sequence of coded bits may be encoded using a convolutional code.

The method may further comprise generating soft bits based the first and/or the second sequence of bits for the decoding.

According to a second aspect of the invention, there is provided an apparatus for estimating a communications channel between a transmitter and a receiver, the apparatus comprising: an input configured to receive a first sequence of bits representing a first sequence of coded symbols transmitted over the communications channel; a decoder configured to decode the first sequence of coded symbols using maximum-likelihood based decoding by at least: generating traceback outcomes by tracing backwards the first sequence of bits through a maximum-likelihood based traceback path, the traceback outcomes including a first portion associated with a first traceback depth and a second portion associated with a second traceback depth that is deeper than the first traceback depth; and generating an estimate of at least some information bits coded in first sequence of the coded symbols based on the second portion of the traceback outcomes, and a channel estimator configured to generate a channel estimate of the communications channel based on the first portion of the traceback outcomes.

Further aspects of the present invention and further embodiments of the aspects described in the preceding paragraphs will become apparent from the following description, given by way of example and with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a schematic diagram of a communications system including a transmitter, a receiver and a communication channel.

FIG. **2** illustrates schematically a time representation of data bits at various points in an orthogonal frequency division multiplexing (OFDM) based system.

FIGS. **3**A and **3**B each illustrate a partial trellis diagram for a 4-state rate-1/2 convolutional coding scheme.

FIGS. **4**A-**4**C each illustrate the information bit error rate (BER) as a function of traceback depth in a trellis traceback.

FIG. **5** illustrates a method of generating a channel estimation according to the present disclosure.

FIG. **6** illustrates three iterations of the method of FIG. **5** on an OFDM data packet.

DETAILED DESCRIPTION OF EMBODIMENTS INTRODUCTION

Described herein are a method and an apparatus for estimation of a wireless communications channel between a transmitter **110** and a receiver **120**. FIG. **1** illustrates a simplified schematic diagram of a communications system. As illustrated in FIG. **1**, the transmitter **110** includes an encoder **112** which encodes input information bits **114** into coded bits **116**, and a modulator **118** which modulates the coded bits **116** into a suitable signal format at radio-frequency (RF) frequencies for wireless transmission as a via a transmitting antenna. The RF signal is transmitted wirelessly through a communications channel **150**. In practice, the effects of the communication channel **150** are to distort the RF signal by, for example, introducing noise, timing jitters and frequency offsets. The role of the encoder **112** is to add redundancy to the transmitted data so that errors due to such signal distortions can be corrected after the distorted RF signal is received and demodulated at the receiver **120**.

At the receiver **120**, a receiving antenna receives the distorted RF signal. The receiver **120** includes a demodulator **122** to demodulate the received RF signal to generate received bits **124**. The received bits **124** generally differ from the coded bits **116** due to the signal distortions. The receiver **120** also includes a decoder **126** to decode the received bits. The decoding process generates an estimate **128** of the information bits **114** by essentially reversing the operation of decoder and, in doing so, attempting to recover the information bits **114** by counteracting the effects of the signal distortions. The following description refers particularly to convolutional coding but is applicable to other types of coding, such as turbo coding and low-density parity-check (LDPC) coding.

A skilled person would appreciate that, for simplification, there may be other components which are omitted from FIG. **1**, such as an interleaver/de-interleaver, a scrambler/descrambler, a data/symbol mapper, fast Fourier transform (FFT) or inverse FFT units and a puncturer/depuncturer.

One or more of the components of the receiver **120** may be implemented as software, such as a computer program including instructions stored in a non-transitory computer-readable medium and executable by the one or more processors. In one example, the non-transitory computer-readable medium is a memory or storage module, such as volatile memory including a random access memory (RAM), non-volatile memory including read-only memory (ROM), or a harddisk. The one or more processors may be one or more computer processing units (CPUs). Alternatively or additionally the one or more of the components of the receiver **120** may be implemented as hardware, such as using one or more digital signal processors (DSPs), application-specific integrated circuits (ASICs) or field-programmable gate arrays (FPGAs).

To improve the accuracy of the information bit estimate **128** generated by the decoder **126**, the receiver **120** may include a channel estimator **130** to at least partially compensate the effects of the channel As mentioned in the background, the channel estimator **130** may initially rely on the preamble of the received packet to provide a channel estimate **132** to assist the demodulator **122** to demodulate at least the earlier parts of the payload (i.e. the data bearing segment of the data packet following the preamble). Once decoding is performed on the earlier parts of the payload, the channel estimator **130** may update the channel estimate **132** based on the decoder outcomes (i.e. the information bit estimate **128** which are then re-encoded and/or the estimates **134** of the coded bits) as they are released from the decoder **126**. Updated channel estimates **132**, which reflect more accurate or changed channel characteristics, may then be provided to the demodulator **122** for use in demodulating the later parts of the payload.

In orthogonal frequency division multiplexing (OFDM) communication systems, each data packet is encoded and modulated to include multiple OFDM symbols. As FIG. **2** illustrates, each OFDM symbol corresponds to a block or set of information bits **114** at the transmitter **110** to be encoded by the encoder **112** as well as corresponding to their estimates generated by the decoder **126**. In some cases, each set of received bits **124** is processed in the receiver **120** on a symbol-by-symbol basis. In others, the received bits **124** may be processed other than on a symbol-by-symbol basis. For example, received bits **124** may be processed in blocks of multiple symbol and/or multiple subcarriers, or processed based on the entire packet. In the description that follows, a receiver processing received bits on a symbol-by-symbol basis is described, but a skilled person would appreciate that similar principles apply to a receiver which processes received bits on a basis other than a symbol-by-symbol basis.

Traceback

At the decoder **126**, decoder outcomes include estimates **128** of the information bits **114** (hereinafter "information bit estimate(s)") as well as estimates **134** of the coded bits **116** (hereinafter "coded bit estimate(s)"). As illustrated in FIG. **1**, the coded bit estimate **134** may be provided to the channel estimator **130** for generating an updated channel estimate **132**. Decoder outcomes are released based on traceback outcomes generated in a traceback process (or trellis traceback). The traceback process is described in further detail as follows using Viterbi decoding as an example, though a skilled person would appreciate that the description is applicable to any maximum-likelihood based decoding.

FIG. **3**A illustrates a partial trellis **300** corresponding to a section of an OFDM symbol for a 4-state rate-1/2 code. In some embodiments, when a received OFDM symbol is processed at the receiver **120**, a block of "soft bits" pertaining to that OFDM symbol may be generated and provided to the decoder **126**, such as a Viterbi decoder. The Viterbi decoder is a finite-state machine that allows it to update survivor metrics with this new block of "soft bits". The state of the decoder is advanced by a number of epochs **302** equal to the number of information bits **114** encoded into the OFDM symbol. On each branch of the trellis are two pieces of information—the input label **304** and the output label **306**. In the case of a rate-1/2 code, the input label **304** corresponds to a single information bit (b) and the output label **306** consists of two coded bits (dd). The input label bits are useful to the higher layers of the stack (e.g. according to the layer of stacks in the Open Systems Interconnection (OSI) model) and are passed up for further processing. The output label bits are those used to, in the case of quadrature amplitude modulation (QAM), select I/Q symbols at the transmitter and are therefore of interest to the channel estimator **130** for generating channel estimates.

From the encoding perspective, each encoder epoch **302** towards the right in FIG. **3**A corresponds to a new input (b) taken sequentially from the information bits **114** into the encoder **112**, resulting in a set of output bits (dd) forming the coded bits **116** and a new state (**00**, **01**, **10** or **11**). The output bits (dd) are a function of the current state and the new input (b) Similarly, the new state is also a function of current state and the new input. For example, in a 4-state rate-1/2 code, as illustrated in FIG. **3**B, each new input bit (b) results in a transition to a new state and an output of two bits (dd) dependent on the original state and the input bit (b). For the example of FIG. **3**B, starting from an initial state **00**, the input bits of **110** cause traversal of the encoder **112** to states **01**, **10** and **00**, producing output bits **01 00 10**. A skilled person would appreciate that these state transitions and output bits can be expressed by look-up tables or a trellis.

From the decoding perspective, a list of surviving paths is kept, one for each state in the trellis. Each surviving path is of a certain, common, depth. The depth is measured in a number of encoder epochs **302**. In a Viterbi decoder, as a newly received OFDM symbol is processed, the surviving paths are created by adding new epochs (corresponding to the newly received OFDM symbol) to the head of the trellis memory. This may be performed by the add-compare-select accumulation of surviving paths and their associated path metrics. In some embodiments, a puncturer is used at the transmitter side to reduce the number of coded bits produced by the encoder **112** to increase the effective code rate. In these embodiments, at the receiver side, a de-puncturer inserts de-punctured bits before the received bits are decoded by the decoder **126**.

As illustrated in FIG. **4**A, from time to time, the trellis **300** is traversed in reverse time in a traceback process to generate traceback outcomes **401**, which, in the case of a 4-state rate 1/2 code, include estimates of the input bits (b) and the output bits (dd) at each encoder epoch. Estimates of the output bits (dd) correspond to estimates **134** of the coded bits **116**, whereas estimates of the input bits (dd) correspond to estimates **128** of the information bits **114**. In general, the traceback process begins from the end **402** of the survivor memory (i.e. from the most recently added information) and traverses this memory in the traceback direction **403** (i.e. in reverse time). Each epoch traversed corresponds to an encoder epoch which, in the case of typical OFDM standards, corresponds to a single information bit and 1 or more coded bits.

The traceback process visits a sequence of state transitions or branches contained in the Viterbi survivor memory. For each epoch a branch (corresponding uniquely to a transition between a pair of states either side of the epoch) is identified as being the transition that mostly likely occurred at the encoder **112** at this epoch. Effectively the Viterbi traceback process attempts to visit each encoder trellis branch in reverse order to that of the encoder **112** in a maximum-likelihood based path to achieve maximum-likelihood based decoding.

As each epoch is traversed in the traceback, traceback outcomes **401** can potentially be released from the decoder **126** as the decoder outcomes. However, unless the terminating state is known (e.g. in the middle of a packet), earlier-generated part(s) of the traceback outcomes **401** at shallow traceback depths may be subject to high information bit error rate (BER) **410**. For example, parts **404** and **406** of the traceback outcomes **401** correspond to, respectively, an unacceptable and an elevated information BER **410**. A skilled person would therefore appreciate that, in Viterbi traceback, these earlier-generated parts **404** and **406** of the traceback outcomes **401** at a shallow traceback depths are disregarded and prevented from being released as decoder outcomes since they are subject to higher information BER **410** than those generated at further or deeper traceback depths in the traceback process from a later-generated part **408** of the traceback outcomes **401**, which corresponds to an acceptable information BER. That is, only selected traceback outcomes **412** may be released as decoder outcomes, whereas some traceback outcomes **414** are disregarded (see FIG. **4**B).

As illustrated in FIG. **4**B, a known rule of thumb is to disregard or prevent release of the early-generated bits in the traceback process for generating decoder outcomes. For example, only traceback outcomes at traceback depth of 7N or greater are released, where N is the constraint length of the chosen convolutional coding. The released estimates of output bits (dd), which correspond to the coded bit estimates **134**, may be provided to the channel estimator **130** and used to generate a channel estimate **132** Similarly, the released estimates of input bits (b) correspond to the information bit estimates **128**. For a 64-state code, and using this rule of thumb, the first 42 bits from the traceback are disregarded and only bits traversed later in the traceback process are released as decoder outcomes. The disadvantage of holding off the release of decoder outcomes is the delay in providing updated channel estimate **132**.

Release of Traceback Outcomes for Channel Estimation

The present disclosure provides that the estimates of output bits (dd) (i.e. coded bit estimate **134**) for generating channel estimate **132** and the estimates of input bits (b) for generating information bit estimate **128** may be released from different parts, hence at different times, of the traceback outcomes **401**.

In one embodiment, as illustrated in FIG. **4**C, the estimates of output bits (dd) (i.e. the coded bit estimate **134**) for use by the channel estimator **130** are released from the earlier-generated part **406** of the traceback outcomes **401**, which correspond to an elevated (but not unacceptable) information BER, than the later-generated part **408** of the traceback outcomes **401**, which corresponds to an acceptable information BER and are released for generating the information bit estimates. As in FIG. **4**B, in the embodiment illustrated in FIG. **4**C, the traceback depth at which the information BER is considered acceptable may be defined by the 7N rule-of-thumb. The traceback depth at which the information BER is considered elevated (but not unacceptable) may be defined by another criteria based similarly on the traceback depth. For example, a traceback depth from 2N to 7N may be applied to identify traceback outcomes with an elevated information BER. Traceback outcomes from within the earlier-generated part **406**, which corresponds to traceback depths subject to an elevated information BER, are disregarded and prevented from being released for generating any information bit estimate. Similarly, traceback outcomes **401** from within the earliest-generated part **404**, which corresponds traceback depths subject to an unacceptable information BER, are still disregarded and prevented from being released for generating either estimate. As mentioned above, coded bit estimates **134** released earlier in the traceback outcomes **401** may in turn be used for generating channel estimate **132** by channel estimator **130**.

Whilst the part **406** is characterised by an elevated information BER **410**, the more quickly available, but reduced quality coded bit estimates **134** in the part **406** are acceptable for use in channel estimation, because the channel estimation process is understood to have increased tolerance to bit errors than the information bit estimate. For example, it is understood that a bit error in the sequence of information bits will result in media access control (MAC) frame failure due to the Frame-Check-Sequence (or FCS), whereas, in comparison, a bit error in the channel estimate training symbols is not understood to be fatal due to time and frequency domain smoothing of the channel estimate **132** and the robustness of the error control code to be applied subsequently.

The advantage of early release of traceback outcomes is that channel estimation can be started earlier than if channel estimation is generated based on coded bit estimate from later traceback outcomes. Consequently, the early release of traceback outcomes improves the delay in providing channel estimates **132**.

Further, early release of traceback outcomes for channel estimation purposes has the advantage that the received OFDM symbols used for channel estimation are closer to the wavefront of the received OFDM symbols, meaning that the channel estimates used for log-likelihood ratio (LLR) calculations are less aged (i.e. "younger") than if the channel estimates are generated based on the coded bit estimate from a later part of the traceback outcomes. Relying on younger channel estimates is particularly important in mobile applications where the channel is changing rapidly during a packet.

The earlier parts **404** and **406** and the later part **408** of the traceback outcomes are generally of a different length and, in an OFDM system, each correspond to one or more OFDM symbol periods. The respective lengths of parts **404**, **406** and **408** depend on the actual information BER characteristics of the communications channel in question. As illustrative examples, for a wireless link:

- An acceptable information BER is below approximately 10^{-6}.
- An elevated information BER is below approximately 10^{-3} and above approximately 10^{-6}.
- An unacceptable information BER is approximately above 10^{-3}.

Other BER values are also possible.

FIG. **5** illustrates a method **500** of the present disclosure in estimating the communications channel between a transmitter and a receiver. The transmitter is configured to transmit data including (i−1)-th coded bits generated by encoding (i−1)-th information bits and i-th coded bits generated by encoding i-th information bits. The (i−1)-th coded bits are earlier bits than the i-th coded bits. The (i−1)-th coded bits and the i-th coded bits may be of different length. In the case of an OFDM-based system, the (i−1)-th coded bits may include one or several OFDM symbols. Similarly, the i-th coded bits may include one or several OFDM symbols. In other words, i and (i−1) may be, but are not necessarily, treated as the OFDM symbol index.

The disclosed method includes the step **502** of receiving data including (i−1)-th received bits corresponding to the (i−1)-th coded bits and i-th received bits corresponding to the i-th coded bits. In general, the received bits and coded bits are different due to signal distortion arising from channel effects. The disclosed method also includes the step **504** of decoding the received data using maximum-likelihood based decoding, which includes generating traceback outcomes by tracing backwards through a maximum-likelihood based path across at least the i-th received bits and thereafter the (i−1)-th received bits. The generated traceback outcomes include a first part **406** corresponding to the i-th received bits and a second part **408** corresponding to the (i−1)-th received bits. Since traceback outcomes are generated in a traceback process in reverse time, the first part **406** of the traceback outcomes corresponding to the i-th received bits are generated earlier than the second part **408** of the traceback outcomes corresponding to the (i−1)-th received bits. The disclosed method also includes the step **506** of generating a channel estimate of the communications channel based on at least a portion of the first part **406** of the traceback outcomes, and the step **508** of generating an estimate of the (i−1)-th information bits based on at least a portion of the second part **408** of the traceback outcomes.

In the case of an OFDM system, in one scenario, the first part **406** (i.e. the part associated with an elevated information BER) of the traceback outcomes may be several OFDM symbols long. In this scenario, the channel estimate can be generated based on a portion of the first part **406**, such as the output bits of the traceback outcomes that belong to one of the several OFDM symbols. For example, it may improve processing speed of the receiver where the channel estimate is generated based on an estimate of the OFDM symbol released earliest within the first part **406** of the traceback outcomes **410**. The channel estimate may be based on any portion (e.g. the first part **406** or the second part **408**), with the expectation that using a larger traceback depth introduces more latency in the processing. In another scenario, the first part **406** may be only one OFDM symbol long, in which case the channel estimate is generated based on output bits generated in the entire portion of the first part **40** of the traceback outcomes. Similarly, in one scenario, the second part **408** of the traceback outcomes **410** may be one or several OFDM symbols long.

In one arrangement, the step **506** of generating a channel estimate commences after or soon after tracing backwards through the i-th received bits and before completion of tracing backwards through the (i−1)th received bits. That is, channel estimation may commence as soon as the first part **406** of the traceback outcomes **410** is available. Early release of traceback outcomes **410** associated with elevated but not unacceptable information BER may provide early commencement of channel estimation. The step **508** of generating an estimate of the (i−1)-th information bits commences after completion of tracing backwards through the (i−1)th received bits.

More generally, and referring to FIG. **4**C, generating traceback outcomes include tracing backwards through firstly (i+1)-th received bits (to generate a third part **404** of the traceback outcomes **410**), then the i-th received bits (to generate the first part **406** of the traceback outcomes **410**), and thereafter the (i−1)-th received bits (to generate a second part **408** of the traceback outcomes **410**). The (i+1)-th received bits correspond to (i+1)-th coded bits generated at the encoder **112** based on (i+1)-th information bits. The third part **404** of the traceback outcomes **410** corresponding to the (i+1)-th received bits is however disregarded due to their association with an unacceptably high information BER. Accordingly, the step **506** of generating a channel estimate may include disregarding a third part **404** of the traceback outcomes **410** that correspond to the (i+1)-th received bits. This third part **404** is also disregarded for the purposes of generating the information bit estimate **128**.

In one scenario, the length of the third part **404** or the (i+1)-th received bits is 2N. That is, only traceback outcomes beyond the length of 2N are released due to unacceptably high information BER. Other lengths of the third part **404** are also possible.

In some arrangements, the combined length of the (i+1)-th received bits and i-th received bits is no less than approximately a traceback length of approximately 7N, where N is the encoding constraint length of the chosen convolutional coding. In these arrangements, therefore, the generation of the information bit estimate **128** has at least a lag time corresponding to 7N.

Updating Channel Estimate

When one or more new symbols of a data packet are received and added to the start of the trellis memory, the method **500** may be repeated to provide an updated channel estimate by commencing from the new start of the trellis memory. Each iteration of the method **500** also advances the position of the data packet at which the information bit estimate can be provided.

FIG. **6** shows an example of three iterations of the method **500** during reception of an OFDM data packet. For simplification, the data packet in this example includes OFDM symbols (i−1), i, (i+1), (i+2) and (i+3) each lasting a single OFDM period. That is, in this example, (i−1), i, (i+1), (i+2) and (i+3) can also be treated as OFDM symbol index. A skilled person would appreciate that the method **500** may be applied to iterate on data packets having portions of different sizes (such as that shown in FIG. **4**C). Also, to illustrate the relevant principle, only three iterations to be applied towards a middle portion of a data packet are shown. A skilled person would appreciate that more iterations before and/or after these iterations may be required depending on the length of the entire data packet.

At iteration j=1, OFDM symbols (i−1), i and (i+1) have been received. The method **500** is applied to the partially received data packet, including tracing backwards through a maximum-likelihood based path across firstly symbol (i+1), then symbol i and thereafter symbol (i−1). At this iteration, traceback outcomes corresponding to symbol (i+1) are disregarded. A channel estimation is generated based on traceback outcomes corresponding to symbol i (step **506**), and an information bit estimate may be generated based on traceback outcomes corresponding to symbol (i−1) (step **508**).

At iteration j=2, an additional OFDM symbol (i+2) has been received. The method **500** is applied to the partially received data packet, including tracing backwards through a maximum-likelihood based path across firstly symbol (i+2), then symbol (i+1) and thereafter symbol i. At this iteration, traceback outcomes corresponding to symbol (i+2) are disregarded. An updated channel estimation is generated based on traceback outcomes corresponding to symbol (i+1) (step **506**), and an information bit estimate is generated based on traceback outcomes corresponding to symbol i (step **508**).

At iteration j=3, a further OFDM symbol (i+3) has been received. The method **500** is applied to the partially received data packet, including tracing backwards through a maximum-likelihood based path across firstly symbol (i+3), then symbol (i+2) and thereafter symbol (i+1). At this iteration, traceback outcomes corresponding to symbol (i+3) are disregarded. A further updated channel estimation is generated based on traceback outcomes corresponding to symbol (i+2) (step **506**), and an information bit estimate is generated based on traceback outcomes corresponding to symbol i+1 (step **508**).

Now that embodiments of the present disclosure are described, it should be apparent to the skilled person in the art that the described wireless receiver has the following advantages:

- Channel estimation can be commenced earlier since decoding outcomes generated during the earlier of the traceback process are used. This reduces the time lag in ultimately providing the estimates of the information bits.
- The earlier channel estimation also allows more time-relevant (i.e. less aged) channel estimates for use with decoding the received bits. In situations where the channel changes rapidly, for example, in a mobile environment, this facilitates more accurate decoding results.
- For the purposes of channel estimation, a data re-encoding step at the receiver is not necessary, since the traceback outcomes intrinsically include coded bit estimates for use by the channel estimator.

It will be understood that the invention disclosed and defined in this specification extends to all alternative combinations of two or more of the individual features mentioned or evident from the text or drawings. For example, a 4-state rate-12/convolutional coding scheme is described, other convolutional coding schemes may well be suitable. All of these different combinations constitute various alternative aspects of the invention.

What is claimed is:

1. A method of estimating a communications channel between a transmitter and a receiver, the method comprising:

receiving at the receiver a first sequence of bits representing a first sequence of coded symbols transmitted over the communications channel; and

decoding the first sequence of coded symbols using maximum-likelihood based decoding including:

generating traceback outcomes by tracing backwards the first sequence of bits through a maximum-likelihood based traceback path, the traceback outcomes including a first portion associated with a first traceback depth and a second portion associated with a second traceback depth that is deeper than the first traceback depth;

generating a channel estimate of the communications channel based on the first portion of the traceback outcomes; and

generating an estimate of at least some information bits coded in the first sequence of coded symbols based on the second portion of the traceback outcomes;

wherein generating the channel estimate of the communications channel commences after generation of the first portion of the traceback outcomes and before completion of the second portion of the traceback outcomes.

2. The method of claim **1** wherein the first portion is subject to a first information bit error rate (BER) and the second portion is subject to a second information BER that is lower than the first information BER.

3. The method of claim **1** further comprising disregarding any estimate of the information bits generated based on the first portion of the traceback outcomes.

4. The method of claim **1** wherein the traceback outcomes includes a third portion that is associated with a third traceback depth that is shallower than the second traceback depth, and that is subject to a third information BER that is higher than the first information BER, the method further comprising:

disregarding any estimate of information bits generated based on the third portion of the traceback outcomes; and

disregarding any estimate of a transmitted coded symbol generated based on the third portion of the traceback outcomes.

5. The method of claim **1** wherein the step of generating a channel includes generating an estimate of at least one of the first sequence of transmitted coded symbols based on the first portion of the traceback outcomes.

6. The method of claim **1** wherein the step of generating a channel includes:

generating an estimate of information bits coded in the coded symbols based on the first portion of the traceback outcomes; and

re-encoding the estimate of the information bits to form re-encoded symbols.

7. The method of claim **1** further comprising:

receiving at the receiver a second sequence of bits representing a second sequence of coded symbols and including at least part of the first sequence of bits;

decoding the second sequence of coded symbols using maximum-likelihood based decoding including:

generating further traceback outcomes by tracing backwards the second sequence of bits through a maximum-likelihood based traceback path, the further traceback outcomes including a fourth portion associated with a fourth traceback depth and a fifth portion associated with a fifth traceback depth that is deeper than the fourth traceback depth,

generating an updated channel estimate of the communications channel based on the fourth portion of the further traceback outcomes; and

generating an estimate of at least some information bits coded in the second sequence of coded symbols based on the fifth portion of the further traceback outcomes.

8. The method claim **7** further comprising disregarding any estimate of the information bits generated based on the fourth portion of the further traceback outcomes.

9. The method of claim **7** wherein the further traceback outcomes includes a sixth portion that is associated with a sixth traceback depth that is shallower than the fourth traceback depth, and that is subject to a sixth information BER that is higher than the fourth information BER, the method further comprising:

disregarding any estimate of information bits generated based on the sixth portion of the further traceback outcomes; and

disregarding any estimate of a transmitted coded symbol generated based on the sixth portion of the further traceback outcomes.

10. The method of claim **1** wherein the second traceback depth is no less than approximately 7N, where N is the encoding constraint length.

11. The method of claim **7** wherein the fifth traceback depth is no less than approximately 7N, where N is the encoding constraint length.

12. The method of claim **1** wherein each of the first portion and the second portion correspond to one or more OFDM symbols.

13. The method of claim **7** wherein each of the fourth portion and the fifth portion correspond to one or more OFDM symbols.

14. The method of claim **1** wherein the first sequence of coded bits are encoded using a convolutional code.

15. The method of claim **7** wherein the second sequence of coded bits are encoded using a convolutional code.

16. The method of claim **1** further comprising generating soft bits based the first sequence of bits for the decoding.

17. The method of claim **7** further comprising generating soft bits based the second sequence of bits for the decoding.

18. An apparatus for estimating a communications channel between a transmitter and a receiver, the apparatus comprising:

an input configured to receive a first sequence of bits representing a first sequence of coded symbols transmitted over the communications channel;

a decoder configured to decode the first sequence of coded symbols using maximum-likelihood based decoding by at least:

generating traceback outcomes by tracing backwards the first sequence of bits through a maximum-likelihood based traceback path, the traceback outcomes including a first portion associated with a first traceback depth and a second portion associated with a second traceback depth that is deeper than the first traceback depth; and

generating an estimate of at least some information bits coded in first sequence of the coded symbols based on the second portion of the traceback outcomes, and

a channel estimator configured to generate a channel estimate of the communications channel based on the first portion of the traceback outcomes, wherein generation of the channel estimate of the communications channel commences after generation of the first portion of the traceback outcomes and before completion of the second portion of the traceback outcomes.

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